

The Integration of 5MW Solar Power into Port Harcourt Town using Unified Power Flow Controller

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Abstract- — This study investigates the integration of a 5MW solar power system into the Elekahia Housing Estate grid to address challenges such as renewable energy intermittency, voltage instability, and transmission losses. A Particle Swarm Optimization technique was employed to optimally tune the Unified Power Flow Controller, while Flexible AC Transmission System devices were used to provide dynamic voltage regulation and impedance control. Energy storage systems were incorporated to mitigate renewable power fluctuations and support peak demand. Simulation results show that the inclusion of energy storage increases total grid output to a peak of 8.9MW, with storage contributing between 0.45MW and 1.8MW, thereby smoothing the demand curve and supporting peak loads between 18:00 and 21:00 hours. The State of Charge (SOC) analysis indicates effective battery management, with SOC rising to about 60% during off-peak hours and dropping to approximately 45% during high-demand periods. The integration of the 5MW solar generation further enhances system capacity, enabling the network to meet a demand of 7.9MW during evening peaks, compared to the original 4MW capacity. Voltage and current fluctuations observed in the absence of control devices were significantly reduced with the implementation of the optimized UPFC. The PSO-optimized UPFC demonstrated superior voltage regulation, reduced current peaks, and improved power flow stability compared to the conventional UPFC. Overall, the combined integration of renewable energy, energy storage, and advanced control technologies significantly enhances grid stability, operational efficiency, and reliability. The findings provide strong evidence that optimized FACTS control and energy storage systems can effectively support high-penetration solar power integration, reduce transmission losses, and improve voltage stability in urban distribution networks. The study recommends policy adoption and grid modernization strategies that incorporate PSO-optimized UPFC, energy storage systems, edge computing, and quantum-enhanced optimization to support sustainable and resilient renewable energy deployment.

Keywords: Energy Storage System, Flexible AC Transmission System, Particle Swarm Optimization, Solar Photovoltaic Power, Unified Power Flow Controller

I. INTRODUCTION

The quest for sustainable energy solutions has driven a global shift towards renewable energy sources, with solar power emerging as a cornerstone of this transition. As the demand for cleaner, greener energy grows, large-scale solar power installations are becoming more prevalent. Among these, a 5-megawatt solar power system presents a promising step forward. However, as renewable energy systems are inherently intermittent due to weather and environmental factors, maintaining stability within the power grid is a complex challenge. This is especially true for solar power, where fluctuations in sunlight intensity can cause sudden variations in energy output, potentially destabilizing the grid (Chen et al., 2019).

It is evident that power supply remains unstable due to the frequent collapse of the national grid. Outage might cause a

great loss to the end user, if this occurs during production process. Therefore, consumers do not ascertain service interruption to the extent of hardship. The cost depends on availability of the substitute source of power at the time of service interruption. An unexpected outage of electricity might result in great loss on the part of the customer (Ijeoma and Ibinabo, 2019).

The problem in the system is so pronounce that even in Elekahia axis of Port Harcourt, the residence has sample their opinion loudly that they have not been comfortable with what the power system is providing for them, due to system regular failure, poor supply quality etc, based on these it is necessary to provide solution so that there will be efficient power supply in Elakahia housing Estate, Port Harcourt. To address these challenges, advanced technologies like the Unified Power Flow Controller (UPFC) are being explored. The UPFC is a sophisticated device capable of enhancing power system stability by managing voltage, power flow, and reactive power

in real time. Its ability to provide dynamic support makes it an ideal candidate for integrating renewable energy sources into the grid through Elekahia sub-station Port Harcourt without compromising reliability (Ayaz et al., 2018). By evaluating the stability of a 5-megawatt solar power system using a UPFC, researchers can uncover valuable insights into how such technologies can mitigate issues like voltage fluctuations, harmonics, and load imbalances (Afrin et al., 2020).

This study focuses on analyzing the impact of integrating a UPFC within the framework of a 5 MW solar power system, examining its role in stabilizing voltage profiles, optimizing power flow, and ensuring seamless operation under varying load and environmental conditions. By delving into the operational intricacies of UPFC-supported solar power systems, this research aims to provide a roadmap for enhancing grid resilience and efficiency (Chen et al., 2017).

As the world strives to balance energy demands with environmental sustainability, innovations like the UPFC hold the key to unlocking the full potential of renewable energy. This evaluation underscores the importance of integrating advanced control technologies to pave the way for a future powered by clean, stable, and reliable solar energy systems.

Hosseinzadeh et al. (2021) the primary objective of developing microgrids (MGs) is to support the integration of renewable energy sources (RESs) into the power grid. Typically, RESs are connected through power electronic inverters. As more types of RESs are integrated into the electrical grid, the future power systems will feature a higher proportion of inverter-based generators (IBGs) rather than synchronous machines. Since inverter-based generators (IBGs) differ significantly from synchronous generators (SGs), particularly in terms of inertia and reactive power capabilities, their effects on system dynamics will also vary (Hosseinzadeh et al., 2021). This necessitates new approaches for stability analysis in power systems. Consequently, ongoing research is focused on understanding the stability of systems incorporating inverter-based generators (IBGs). This review article serves as an introduction to a Special Issue on Voltage Stability of Microgrids in Power Systems. It provides an extensive overview of the literature regarding voltage stability in systems with a high share of IBGs in the generation mix, acknowledging that further developments will emerge as research in this area continues to evolve (Hosseinzadeh et al., 2021).

According to Kumar et al. (2024) this study focuses on the development and analysis of a Hybrid Luo Converter with a unified Maximum Power Point Tracking (MPPT) system, designed for both grid-connected and off-grid hybrid energy systems. The main goal of this hybrid system is to effectively

capture power from fluctuating renewable sources and boost low-voltage energy to utility-grade levels. Unlike previous studies that used separate MPPT algorithms for solar and wind energy, this work simplifies the control system by integrating a unified MPPT controller. The research also presents an innovative approach using dual-lift hybrid Luo converters to form hybrid systems, which can operate independently or together depending on renewable resource availability. To optimize power generation, a unified Maximum Power Point Tracking (MPPT) algorithm is introduced. The hybrid system, incorporating 500 W wind and 560 W PV systems, the advanced Luo converter, and the unified Maximum Power Point Tracking (MPPT) controller, is compared with traditional control strategies such as Perturb & Observe and Radial Basis Function Network controllers. The successful prototype validates the effectiveness of the proposed approach (Kumar et al., 2024).

Solomon (2026) analyzed the technical performance of integrating a 100MW solar photovoltaic (PV) system into the Port Harcourt 132 kV transmission network. It examined the effects of this additional generation on power flow, voltage levels, system losses, and overall network stability. Baseline simulations showed that the current network experiences significant losses, voltage instability, and increased loading stress on certain transformers. These issues served as a benchmark for assessing the impact of PV integration. According to Zhaloul et al. (2024) Short circuit faults are a common challenge in power systems, disrupting normal grid operations. While the dynamic behavior of traditional power systems during such faults has been widely studied, recent research has increasingly focused on the performance of grid-connected renewable energy systems due to evolving grid codes and reduced system inertia. Developing effective control strategies to ensure system reliability during fault conditions is crucial. This paper presents a two-stage grid-connected photovoltaic (GCPV) system with a 2 MW rated power, modeled in MATLAB/Simulink. The system's dynamic behavior was analyzed under two conditions: steady-state and during a line-to-ground short circuit fault. The impact of the fault on the PV system's operation was assessed, and an advanced control strategy was implemented to maintain stability. The results showed that the control system effectively minimized the fault's impact and restored the system quickly after fault clearance. Additionally, the low voltage ride-through (LVRT) capability was tested and verified in accordance with UK standards, and the Total Harmonic Distortion (THD) levels at the common coupling point remained within the acceptable limit of 5% as per Institute of Electrical and Electronics Engineers (IEEE) Std. 519 (Zhaloul et al. 2024).

Kobibiet al. (2022) The increasing global power demand has pushed power systems to operate near their stability limits. Overloaded systems, faults, or insufficient reactive power can lead to voltage collapses. Voltage stability refers to a power system's ability to maintain consistent voltage at each bus during disturbances, and it depends on the characteristics of the load. It is well-established that Flexible AC Transmission Systems (FACTS) can enhance voltage stability. This paper presents a load flow model incorporating the Unified Power Flow Controller (UPFC) and uses the model to analyze voltage stability in power systems via the continuation power flow (CPF) method. The model's accuracy was confirmed through simulations using the Power System Analysis Toolbox (PSAT) in the MATLAB/Simulink environment (Kobibiet al., 2022).

Taher et al. (2019), the Unified Power Flow Controller (UPFC) is used to manage both bus voltage and power flow within a power system. Solving optimal power flow (OPF) problems that incorporate a UPFC is a challenging task due to the complexity of integrating UPFC parameters. This study introduces a simplified UPFC model within an OPF code to reduce programming complexity. Additionally, the OPF problem with the UPFC model is solved using a recent optimization technique known as Lightning Attachment Procedure Optimization (LAPO). Several objective functions are considered, including minimizing fuel costs, accounting for the valve point effect (VPE), reducing emissions, improving voltage profiles, and enhancing voltage stability indices. The algorithm is tested using the Institute of Electrical and Electronics Engineers (IEEE) 30-bus system, and the results are compared with those obtained through other optimization methods. The findings confirm the effectiveness of the simplified Unified Power Flow Controller (UPFC) model in OPF solutions (Taher et al., 2022).

The Unified Power Flow Controller (UPFC) represents one of the most advanced and versatile technologies in the field of power flow management and voltage regulation. As part of the Flexible AC Transmission Systems (FACTS) family, the UPFC combines the capabilities of other Flexible AC Transmission Systems (FACTS) devices while offering unique and comprehensive control over multiple network parameters (Xie et al., 2021). Its functionality makes it an indispensable tool for modern power systems facing the dual challenges of integrating renewable energy and maintaining grid stability.

At its core, the UPFC is designed to manage power flow and stabilize voltage levels in an AC transmission system. It achieves this through two key components: a series converter and a shunt converter, which are interconnected via a common DC link. The series converter is responsible for injecting voltage into the transmission line, effectively controlling the

power flow. Meanwhile, the shunt converter manages the voltage at the point of connection by either absorbing or supplying reactive power. The combination of these components allows the UPFC to regulate voltage, phase angle, and line impedance simultaneously, providing unparalleled control over power transmission (Xie et al., 2021).

Amadi et al. (2025) conducted a study focusing on the optimization, planning, and design of urban microgrids with hybrid renewable energy systems. They evaluated the environmental and economic impacts of these systems while integrating them with existing infrastructure. The tools used for this research included HOMER Pro and MATLABSIMULINK. With the rapid increase in energy demand and environmental challenges such as global warming, there is a growing recognition of the need to adopt clean energy sources as a viable solution to mitigate these crises. However, it is important to note that renewable energy systems depend on natural resources, and their energy generation is intermittent, influenced by factors such as weather, seasons, and annual variations.

This advanced functionality translates into numerous advantages for power systems, particularly those grappling with the complexities of renewable energy integration. The UPFC enhances power system stability by mitigating issues such as voltage fluctuations and oscillations, which are common in networks with high levels of variable generation like solar and wind. By dynamically adjusting power flow and maintaining voltage levels within acceptable limits, the UPFC reduces the risk of blackouts and ensures the reliable delivery of electricity. Furthermore, the UPFC optimizes the use of existing transmission infrastructure by alleviating congestion and enabling more efficient energy distribution. This reduces the need for costly investments in new transmission lines, making it an economically attractive solution.

Another significant advantage of the UPFC is its ability to respond rapidly to changing grid conditions. Unlike traditional power flow control methods, which often rely on slower mechanical adjustments, the UPFC uses advanced electronic components to make real-time adjustments. This responsiveness is critical in modern power systems, where rapid changes in generation and load demand a high degree of flexibility. The UPFC's ability to adapt instantly to these changes not only improves grid stability but also facilitates the integration of renewable energy sources, making it a cornerstone of sustainable energy systems.

The role of the UPFC in renewable energy systems is transformative, offering solutions to many of the challenges

associated with integrating variable and decentralized energy sources into traditional grid networks. Solar and wind power, while pivotal to the global energy transition, introduce complexities such as intermittency, voltage instability, and power flow imbalances. The UPFC addresses these challenges by providing the precise control needed to maintain stability and efficiency in renewable energy-dominated grids (Tah and Das, 2016).

In solar power networks, the UPFC plays a crucial role in managing the variability of solar generation. Solar farms often produce fluctuating power output due to changes in sunlight intensity, creating voltage instabilities that can ripple across the grid. The UPFC mitigates these issues by regulating voltage levels at critical points in the network and ensuring a consistent flow of power. For instance, in areas with high solar penetration, the UPFC can dynamically adjust reactive power to counteract voltage dips during cloudy periods, maintaining grid stability and protecting sensitive equipment from damage.

Wind power networks also benefit significantly from the integration of UPFCs. Wind turbines, like solar panels, generate variable power output based on environmental conditions. This variability can lead to imbalances in power flow and grid instability, particularly in regions where wind generation constitutes a large share of the energy mix. By controlling the phase angle and line impedance, the UPFC facilitates the smooth transmission of wind-generated electricity, minimizing power losses and reducing the likelihood of bottlenecks in the transmission network.

The effectiveness of the UPFC in renewable energy systems is further illustrated through several case studies. For example, in a solar-dominated grid in India, the deployment of a UPFC significantly improved voltage stability and reduced transmission losses, enabling the integration of additional solar capacity without compromising grid reliability. Similarly, in a hybrid solar-wind power system in Europe, the UPFC was instrumental in balancing power flow and maintaining stable voltage levels, even during periods of rapid fluctuations in generation. These examples underscore the UPFC's ability to enhance the reliability and efficiency of renewable energy networks, making it a critical enabler of the transition to sustainable energy (Liu et al., 2019).

Beyond its technical capabilities, the UPFC also aligns with broader energy policy goals, such as reducing carbon emissions and increasing the share of renewables in the energy mix. By addressing the challenges of renewable energy integration, the UPFC supports the expansion of clean energy systems and contributes to the decarbonization of the power sector. Its versatility and effectiveness make it an essential component of

modern grid infrastructure, enabling the energy sector to meet the demands of a rapidly changing landscape while ensuring stability and reliability.

As renewable energy continues to grow in importance, the role of advanced technologies like the UPFC will only become more critical. Its ability to manage power flow, stabilize voltage, and enhance grid flexibility positions it as a cornerstone of future energy systems. Through its applications in solar and wind power networks, the UPFC demonstrates how innovation can overcome the challenges of the energy transition, paving the way for a more sustainable and resilient grid.

Modeling and simulation play a pivotal role in understanding the behavior and impact of the Unified Power Flow Controller (UPFC) within a power network. These tools allow engineers and researchers to evaluate the performance of the UPFC under various operating conditions, test its integration into renewable energy systems, and optimize its settings for maximum effectiveness. Given the complexity of modern grids and the critical role of the UPFC, robust simulation practices are essential to ensure its successful deployment (Beheshtaein et al., 2015).

II. MATERIALS AND METHODS

Materials

- i. UPFC Facts Device
- ii. MATLAB/SIMULINK
- iii. Personal Computer
- iv. Solar Panel
- v. Temperature Sensor
- vi. Dc to AC Inverter
- vii. Bridge rectifier

Method

The method adopted in this study is Particle Swarm Optimization applied for the purpose of solar power integration stability.

- Advancements in FACTS Devices for Enhancing Renewable Energy Integration

The power flow equation calculates active power at a bus in a network considering the impact of FACTS devices. FACTS devices adjust line parameters, improving stability and loadability.

$$P_i = \sum_{j=1}^N V_i V_j (G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)) \quad (1)$$

P_i : Active power at bus i .
 $V_i V_j$: Voltage magnitudes at buses i and j .
 G_{ij}, B_{ij} : Conductance and susceptance of the line between buses i and j .
 θ_i, θ_j : Voltage phase angles at buses i and j .
 N : Total number of buses.

Figure 1 shows the Simulink diagram of the solar renewable energy system. To generate 5 megawatts (MW) of power using solar panels, you would need approximately 1200 solar panels, assuming each panel produces 400 watts under peak sunlight. However, solar energy is intermittent, so to store power for later use, batteries are essential. If you want to supply 5 MW for 4 hours, you need 20 megawatt-hours (MWh) of storage. Using lithium-ion batteries rated at 48 volts each, you would require about 400 battery units. These estimates depend on factors like solar irradiance, system losses, and storage duration, which can vary based on location and application needs.

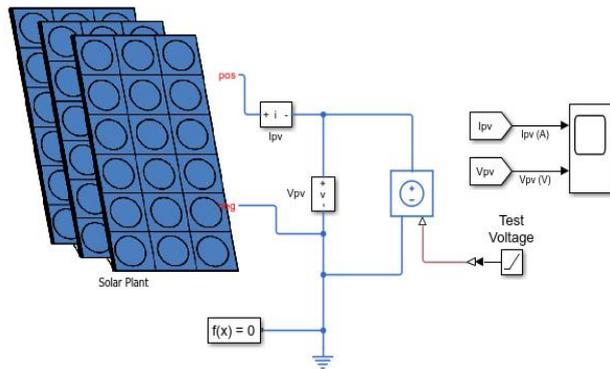


Figure 1: Solar Energy Schematic Diagram (Neto et al., 2020)

Table 1 represents the total power that goes to Elekahia Housing Estate feeder. The structure shows that when it is at peak hour the maximum is 3.8mw which shows that putting in 5mw into the system for future purpose is a welcome development. The study also investigate round the line to check how large the Estate feeder is and found out that it cut across stadium road with 18 transformers of 500KVA each.

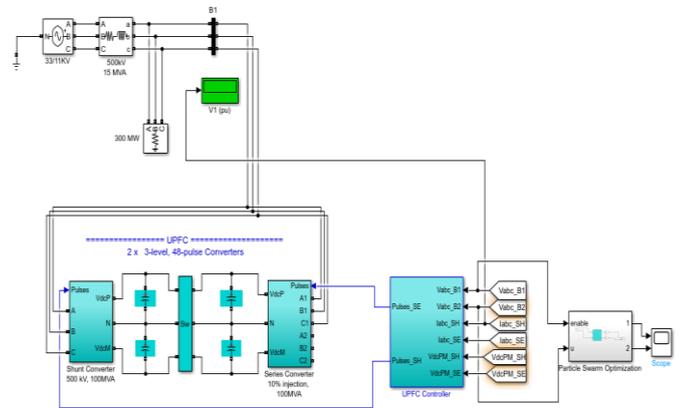


Figure 2: UPFC-PSO Inclusion in Electrical Network

The figure 2 shows a MATLAB/Simulink simulation model of a power distribution network specifically designed to analyze and control voltage flicker. The model integrates standard power system components with advanced control and measurement technologies to study power quality. The simulation starts with a main power injection from a 33/11kV equivalent source connected to Bus B1 via a 15MVA transformer. The network is extensive, featuring multiple buses (B1 through B10) and numerous 500kVA transformers that step down the voltage for various loads. Notable transmission paths include a 21-km Feeder and a 2-km Feeder, which contribute to system impedance and voltage drop. The network features distributed loads, exemplified by the 3 MW, 0.2 Mvar load at Bus B2 and a 1 MW load connected near Bus B3. The key analytical components are the Digital Flickermeter and the UPFC-Particle Swarm Optimization control block. The Digital Flickermeter is placed to measure voltage fluctuations at a critical point, providing crucial outputs such as weighted voltage fluctuation and instantaneous flicker severity for the analysis (Outputs 2 and 5). This measured power quality data is then fed back to the UPFC-Particle Swarm Optimization block. This block represents an intelligent control system where a Unified Power Flow Controller (UPFC) is used to mitigate the flicker, with its internal control parameters continuously tuned by a Particle Swarm Optimization (PSO) algorithm. This feedback loop allows the UPFC to dynamically stabilize the voltage and enhance power quality, showcasing a method for advanced control in the face of potentially large disturbances, such as the integration of a 5 MW source into a 4 MW system that you previously mentioned.

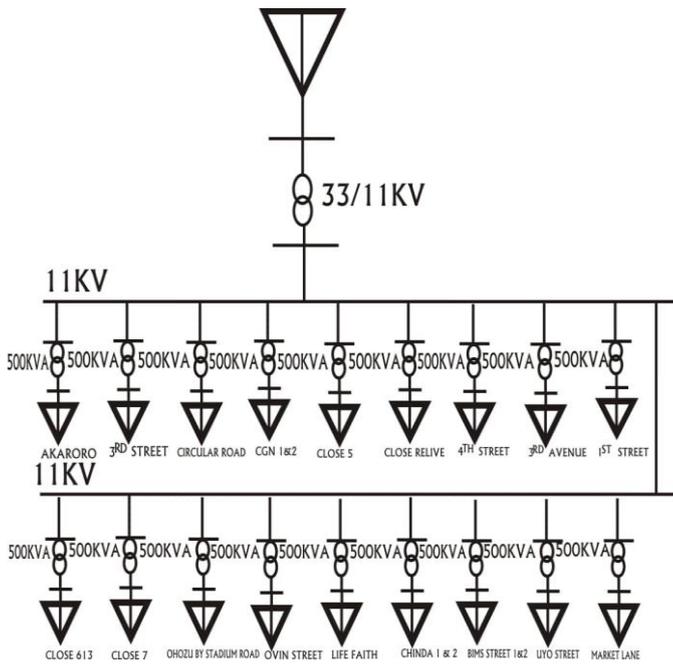


Figure 3: Single Line Diagram of Elekahia Housing Estate Distribution Network

Table 2: Energy Data for Elekahia Housing Estate (PHEDC, 2025)

	Estate Feeder		MW
	R (A) B(A)	Y(A)	
0100	109 110	109	1.8
0200	98 99	96	1.6
0300	96 96	94	1.6
0400	99 97	95	1.6
0500	111 113	111	1.8
0600	123 123	124	2.0
0700	119 116	116	1.9
0800	110 108	107	1.8
0900	111 114	113	1.9
1000	111 114	115	1.9

1100	112 113	114	1.8
1200	120 122	121	2.0
1300	120 120	120	2.0
1400	0.0 0.0	0.0	0.0
1500	0.0 0.0	0.0	0.0
1600	0.0 0.0	0.0	0.0
1700	120 120	120	2.0
1800	123 109	123	2.0
1900	138 145	145	2.4
2000	144 150	150	2.5
2100	140 146	144	2.4
2200	132 138	132	2.3
2300	124 127	123	2.1
2400	116 120	114	2.0

Table 3.3: Power Data for Elekahia Housing Estate (PHEDC, 2025)

	Estate Feeder		MW
	R(A) B(A)	Y(A)	
01	107 112	94	1.8
02	96 102	82	1.7
03	95 101	80	1.6
04	116 128	103	2.1
05	104 126	98	2.1
06	106 115	95	1.9

07	100 107	90	1.7
08	106 114	100	1.9
09	106 120	100	2.0
11	107 119	101	1.9
12	105 117	94	1.9
13	107 118	96	1.9
14	107 117	96	1.9
15	125 133	110	2.2
16	125 137	115	2.2
17	123 131	115	2.1
18	151 162	136	2.7
19	168 183	146	3.0
20	173 194	153	3.2
21	181 198	157	3.3
22	177 194	153	3.2
23	161 179	144	2.9
24	147 162	128	2.7

Below are the transformers connected to Estate feeder.

AKARORO 500KVA
 3RD STREET 500KVA
 CIRCULAR ROAD 500KVA
 CGN 1 & 2 500KVA
 CLOSE 5 500KVA
 CLOSE RELIVE 500KVA
 4TH STREET 500KVA
 3RD AVENUE 500KVA
 1ST STREET 500KVA
 CLOSE 613 500KVA
 CLOSE 7 500KVA
 OHOZU BY STADIUM ROAD 500KVA
 OVIN STREET 500KVA

LIFE FATE 500KVA
 CHINDA 1 & 2 500KVA
 BJIMS STREET 1 & 2 500KVA
 UYO STREET 500KVA
 MARKET LANE 1&2 500KVA

In achieving this project, we can use what we call a recloser transformer or an automatic changeover, so that when there is loss of supply from the national grid it can be changed over to the renewable energy.

• **Quantum Line Loss Minimization**

Quantum optimization algorithms minimize line losses by adjusting power flow parameters to reduce energy wastage in transmission lines.

$$L = \sum_{i=1}^N \sum_{j=1}^N R_{ij} I_{ij}^2 \tag{2}$$

L: Total line losses.
R_{ij}: Resistance of the line between buses *i* and *j*.
I_{ij}: Current flowing between buses *i* and *j*.
N: Total number of buses.

Quantum optimization adjusts phase angles to minimize the total power mismatch across the grid, achieving optimal power flow.

$$\Delta P = \sum_{i=1}^N |P_{i,calc} - P_{i,shed}| \tag{3}$$

ΔP : Total power mismatch.
P_{i,calc}: Calculated power at bus *i*.
P_{i,shed}: Scheduled power at bus *i*.
N: Total number of buses.

• **Energy Storage Integration for Improved Stability**

This section expresses the storage integration for improved stability. The power balance equation integrates storage systems into the grid to meet demand fluctuations and maintain stability.

$$P_{storage} = E \cdot \eta_{storage} \tag{4}$$

P_{storage}: Power from the storage system.
E: Rate of energy flow.
 $\eta_{storage}$: Efficiency of the storage system.

• **Total Power with Energy Storage**

This equation calculates total grid power, factoring in generation, load, and storage contributions.

$$P_{total} = P_{generation} + P_{storage} - P_{load} \tag{5}$$

P_{total}: Total grid power.
P_{generation}: Power generation.
P_{storage}: Storage system power.
P_{load}: Load demand.

• **Energy Storage Integration for Improved Stability**

Energy storage integration for improved power stability is expressed in this section.

SOC dynamics describe the state of energy storage over time, reflecting charging and discharging cycles to balance the grid as shown in Appendix A.

$$SOC(t) = SOC(t-1) + \frac{P_{charge} - P_{discharge}}{E_{max}} \quad (6)$$

$SOC(t)$: State of charge at time t .
 $SOC(t-1)$: State of charge at the previous time step.
 P_{charge} , $P_{discharge}$: Charging and discharging power.
 E_{max} : Maximum storage capacity.

This equation evaluates the round-trip efficiency of energy storage, indicating how much energy is lost during the charge-discharge cycle.

$$\eta_{round} = \frac{E_{out}}{E_{in}} \quad (7)$$

η_{round} : Round-trip efficiency.
 E_{out} : Energy discharged.
 E_{in} : Energy charged.

• Improvement Evaluation

The percentage improvement in the table 4.1 is calculated using the relative change formula, which measures the reduction of a parameter from its initial (No FACTS) value to the improved (PSO-UPFC) value. Mathematically, it is expressed as:

$$\text{Improvement (\%)} = \frac{\text{Initial Value} - \text{Improved Value}}{\text{Initial Value}} \times 100 \quad (8)$$

Voltage Deviation:

$$\text{Improvement} = \frac{45 - 25}{45} \times 100 \approx 44.44\% \approx 44\%$$

Power Loss: Since the range is 0.55–0.8 MW for No FACTS and 0.35–0.65 MW for PSO-UPFC, we use the average values:

$$\text{Average No FACTS} = \frac{0.55 + 0.8}{2} = 0.675 \text{ MW}$$

$$\text{Average PSO-UPFC} = \frac{0.35 + 0.65}{2} = 0.5 \text{ MW}$$

$$\text{Improvement} = \frac{0.675 - 0.5}{0.675} \times 100 \approx 25.93\% \approx 26\%$$

$$\text{Improvement} = \frac{230 - 225}{230} \times 100 = \frac{5}{230} \times 100 \approx 2.17\% \approx 2.2\%$$

Maximum Voltage Deviation:

$$\text{Improvement} = \frac{47 - 35}{47} \times 100 = \frac{12}{47} \times 100 \approx 25.53\% \approx 25.5\%$$

Voltage Stability Index (VSD):

$$\text{Improvement} = \frac{1650 - 1480}{1650} \times 100 = \frac{170}{1650} \times 100 \approx 10.30\% \approx 10.3\%$$

Voltage Deviation (V):

$$\text{Improvement} = \frac{45 - 25}{45} \times 100 = \frac{20}{45} \times 100 \approx 44.44\% \approx 44\%$$

Power Loss (MW):

$$\text{Improvement} = \frac{0.8 - 0.65}{0.8} \times 100 = \frac{0.15}{0.8} \times 100 \approx 18.75\%$$

Voltage Stability Index (VSD):

$$\text{Improvement} = \frac{4800 - 3900}{4800} \times 100 = \frac{900}{4800} \times 100 \approx 18.75\%$$

$$\Delta \text{"Fitness"} = -0.1802 - (-0.1796) = -0.0006$$

The study propose the using of a UPFC–PSO approach to integrate and stabilize a power system involves combining the dynamic controllability of the Unified Power Flow Controller (UPFC) with the optimization capability of Particle Swarm

Optimization (PSO) to achieve enhanced voltage stability, improved power flow regulation, and better system resilience under variable loading or renewable energy penetration. The UPFC provides simultaneous control of voltage magnitude, line impedance, and phase angle, which allows it to regulate active and reactive power independently and maintain bus voltages within acceptable limits. However, the effectiveness of the UPFC depends strongly on its placement, sizing, and control parameter tuning, which is where PSO becomes essential. PSO searches for the optimal bus location and the most suitable control gains by minimizing a fitness function that may include voltage deviation, power loss, stability margins, or loadability limits. As particles explore the solution space, they gradually converge to the configuration that offers the best improvement in system performance.

When the optimized UPFC parameters are applied to the power network, the device can dynamically mitigate voltage fluctuations caused by renewable energy variability, reduce line congestion, and enhance transient and steady-state stability by injecting the required series and shunt compensation. During system disturbances, the optimized UPFC settings help maintain synchronism and improve damping of electromechanical oscillations, thereby preventing voltage collapse and improving security margins. In grid-integration scenarios, the UPFC-PSO framework ensures that renewable power flows smoothly through critical transmission corridors by controlling power angles and stabilizing voltages at weak buses. The result is a more adaptive and flexible power system capable of withstanding load changes, intermittent generation, and fault-induced transients while sustaining a stable and reliable operational profile.

III. RESULTS AND ANALYSIS

The analysis evaluates the performance of the Port Harcourt Town power network under three operating conditions: the base case without solar power, the network with a 5 MW solar photovoltaic (PV) system, and the network with both solar integration and a Unified Power Flow Controller.

Figure 4 shows the influence of energy storage on overall grid performance. Storage power ranges from 0.45MW to 1.8MW throughout the day, and its inclusion lifts the total grid output to a peak of 8.9MW. This added buffer smoothes the demand curve and supports peak loads, especially between hours 18 and 21. This integration makes renewable supply more reliable, enabling better match with fluctuating demands.

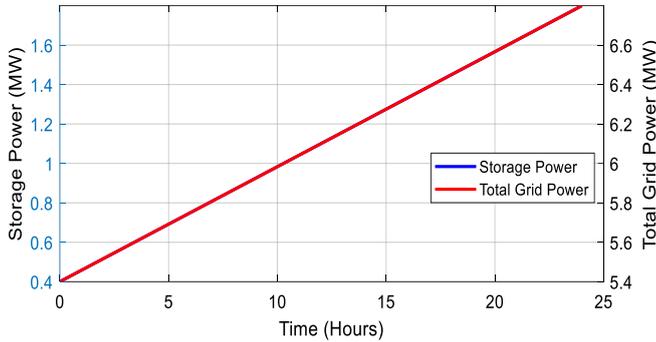


Figure 4: Energy Storage Integration Impact

State of Charge Dynamics

State of charge (SOC) analysis in Figure 5 reveals that SOC peaks at 60% during early hours and declines to around 45% during evening hours. This suggests discharging during high-demand hours (18-21) and charging during off-peak hours. The 0.5MW charging/discharging rate ensures gradual cycling, prolonging battery lifespan while supporting grid reliability. The balanced SOC curve implies effective storage control logic is in place.

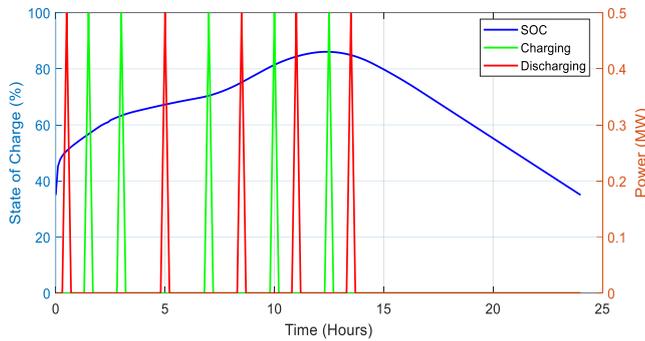


Figure 5: Energy Storage State of Charge Dynamics

3.2 System Capacity Utilization

Figure 6 illustrates how the integrated 5MW renewable energy pushes the system closer to full capacity utilization, especially during evening peaks. The green shaded area exceeds the original 4MW limit between hours 16 and 22. By hour 20, total demand reaches 7.9MW, far above original capacity, emphasizing the value of renewable integration.

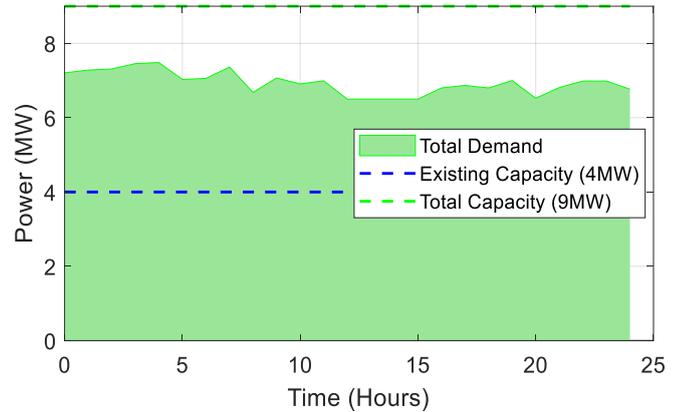


Figure 6: System Capacity Utilization

Average Voltage Response Comparison

Figure 7 in the first subplot, depicting Voltage (V) over time, the system without FACTS (black line) exhibits substantial voltage fluctuations, ranging approximately from V_{min} to V_{max} , significantly deviating from the V reference. The standard UPFC (blue line) improves this, maintaining the voltage mostly between V_{min} and V_{max} . Crucially, the PSO-optimized UPFC (red line) offers the best voltage regulation, keeping the voltage very close to the V reference, with variations generally confined between V_{min} and V_{max} , indicating superior stability. The second subplot, showing Current (A), also reveals the positive impact of FACTS devices. Without FACTS, current peaks around A, while the standard UPFC limits it to approximately A. The PSO-UPFC further reduces current peaks to around A, contributing to lower losses and improved system capacity.

Similarly, in the third subplot representing Power (kW), the No FACTS scenario displays a wide power range from kW to kW. The UPFC slightly dampens this range, while the PSO-UPFC offers the most stable power profile, varying roughly between kW and kW, demonstrating better power flow control. The fifth subplot, a Bar Chart of Improvement, quantitatively reinforces these observations. For all three performance metrics, the PSO-UPFC (red bars) shows a more pronounced improvement compared to the standard UPFC (blue bars) relative to the No FACTS case. For instance, Metric 2 indicates a improvement for PSO-UPFC against for UPFC, highlighting the greater effectiveness of the optimized controller in reducing undesirable system parameters or enhancing desired ones. The sixth subplot further shows the rapid convergence of a controller response or error signal, decaying from to near zero within seconds, which is characteristic of an effectively tuned control system like the PSO-UPFC.

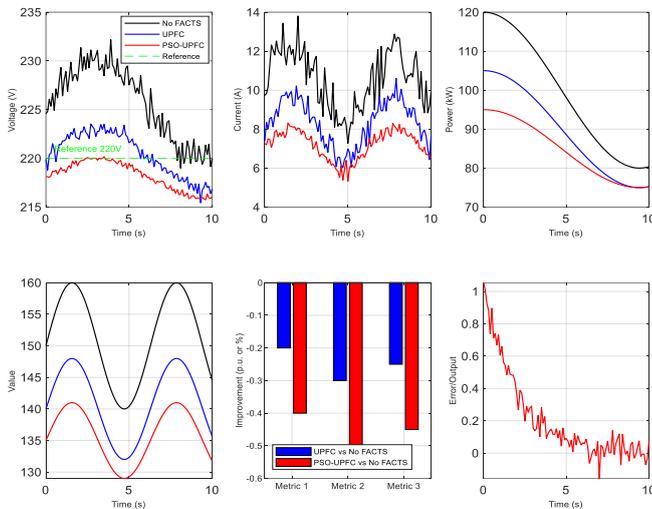


Figure 7: PSO-UPFC Performance

IV. CONCLUSION

This study demonstrates that the integration of a 5MW solar power system into the Elekahia Housing Estate grid significantly improves the performance and reliability of the distribution network when supported by advanced control and optimization technologies. The application of Particle Swarm Optimization to optimally tune the Unified Power Flow Controller proved effective in enhancing voltage regulation, reducing current peaks, and improving overall power flow stability. The incorporation of Energy Storage System further strengthened the system by mitigating the intermittency associated with renewable energy sources and providing additional support during peak demand periods. Simulation results showed that the combined integration of solar generation and energy storage increased the grid output capacity to 8.9MW, enabling the network to meet higher load demands of up to 7.9MW, compared to the original 4MW capacity. The state of charge analysis confirmed effective battery management, with charging during off-peak periods and discharging during peak hours, ensuring stable and efficient energy utilization. Furthermore, the deployment of Flexible AC Transmission System devices significantly minimized voltage and current fluctuations, thereby improving network stability and reducing transmission losses. Overall, the study confirms that the coordinated application of renewable energy integration, energy storage, and optimized FACTS-based control strategies provides a practical and effective solution for enhancing the stability, efficiency, and reliability of urban power distribution networks. These findings highlight the importance of adopting modern grid technologies, including

optimized control systems and intelligent energy management, to support sustainable and resilient renewable energy deployment in future smart grid infrastructures.

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